Draft Project Report

Ground Penetrating Radar for Track Substructure Evaluation

Phases 1-3

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Table of Contents

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Abstract

Ground penetrating radar (GPR) has been employed to assess railway track substructure (ballast, subballast, and subgrade) conditions. GPR involves transmitting radar pulses into the substructure and measuring return signals that have reflected off boundaries between substructure layers with different electromagnetic properties. The principle electromagnetic property of the layers is the *dielectric permittivity*, which is a function of the density, water content, and type of material.

For railroad applications, the GPR equipment is mounted on a hy-rail vehicle with clearance between the antennas and the track surface, which permits continuous measurements to be made from above the top-of-rail at normal vehicle speeds. The antenna configuration and surveying procedures are optimized to account for the influence of ties and rail. Antennas are located at both ends of the ties as well as in the center of the track, so the variations of conditions laterally across the track are seen.

Studies have demonstrated the ability of GPR to distinguish between the different substructure layers as well as areas of trapped water and fouled ballast. Images from field measurements on track will be given to show the GPR capabilities. Observations from inspection trenches excavated under the track are compared with the radar measurements to validate the effectiveness of the technique.

The report demonstrates uses of ground penetrating radar (GPR) to produce cross-sectional images and quantitative indices of track substructure condition on a continuous non-destructive basis. This work will enable improved cost effectiveness of maintenance planning, increased safety, and reduced train service interruptions. The GPR apparatus is installed on a hy-rail vehicle and the radar data is collected while the vehicle is traveling along the track at normal operating speeds. The GPR data are directly processed into cross sectional images for determining causes of problems such as ballast pockets, soft clay, subballast depths, and wet zones. Modeling of the data produces quantitative measures of ballast and other layer thicknesses, density, and water content. Following a description of the GPR methods used, examples are given of some of the radar results obtained on track.

KEYWORDS railroad, ballast, subballast, subgrade, drainage, radar, non-destructive testing, moisture.

Introduction

Track substructure (ballast, subballast, and subgrade) conditions have an important influence in determining track performance and assessing the potential for service interruptions and need to reduce train speed. A significant part of a railroad's track maintenance budget is driven by the rate of deterioration of track geometry. Rough track is caused by movements in the substructure under repeated train loading. The performance is significantly affected by moisture accumulation and thickness of the roadbed layers. Thus the hidden and hard to monitor substructure conditions are important to railway track performance (Selig and Waters, 1994). Modern radar systems can perform these measurements with this resolution at speeds of 100 miles per hour (160 km/hr).

Ground penetrating radar (GPR) has the ability to map railroad track substructure conditions on a continuous, top-of-rail, non-destructive basis. In this study, the antennas were located between the rails as well as at the ballast shoulders beyond the ends of the ties. Substructure conditions were observed such as thickness of the ballast and subballast layers, variations in layer thickness along the track, pockets of water and soft subgrade. In addition, locations and depths of subsurface drainage pipes, trenches, and utilities were identified. The radar equipment was mounted on a hy-rail vehicle moving continuously at speeds ranging from less than 2 mph to more than 25 mph. At 10 miles per hour (16 km/hr) the radar resolution of a few inches horizontally and a fraction of an inch vertically to depths of more than 6 feet (2 m) can be achieved.

The goal of this project is to develop and automatically process Ground Penetrating Radar (GPR) to produce quantitative indices of track substructure condition. Successful achievement of this goal will result in improved cost effectiveness of maintenance planning, increased safety, and reduced train service interruptions. The system requires multiple antennas to show transverse as well as longitudinal variation of the track substructure. The equipment is intended for use on a hy-rail vehicle or a track geometry car.

The scope of work to achieve this specified goal consists of 4 phases. Using existing hardware the first two phases involved exploring the capabilities of ground penetrating radar for railway track, and establishing appropriate apparatus and procedures for collecting and processing the radar data. The need for obtaining radar measurements at multiple positions across the track to portray the three-dimensional nature of the substructure was determined. The ability of modeling the radar data to determine estimates of water content and density of the substructure materials was demonstrated. A variety of radar images was produced which illustrated the potential benefits of radar for determining track subsurface conditions.

The third phase also uses available radar equipment. This is mounted on a hy-rail vehicle. Multiple antenna configurations are established and appropriate configurations are determined. Measurement procedures were defined and calibration procedures developed. Software is designed to process the radar data automatically. Sites representing a variety of subsurface conditions are measured to demonstrate and verify the radar techniques.

Phase 4 involves installing the radar on a hy-rail geometry vehicle and using it to collect radar images from selected BNSF sites. Also in Phase 4, software is developed using radar image modeling techniques from Phase 3 to provide automatic calculation of the depths, densities and moisture content of the substructure layers.

Using radar modeling techniques with the aid of computer simulation, techniques for calculating moisture content, dielectric permittivity (electrical property) and density values are estimated. Development of radar indices will be initiated from a study of the radar images for a variety of subsurface conditions. Indices of substructure conditions were defined.

Ground penetrating radar (GPR) can provide a rapid, nondestructive measurement technique for evaluating railway track substructure condition (Olhoeft and Selig, 2002), (Hyslip, Olhoeft and Smith, 2003). Methods of applying GPR to railways are being developed to provide a continuous evaluation of the track substructure conditions relative to subsurface layering, material type, moisture content and density.

GPR Principles

The GPR method requires transmitting pulses of radio energy into the subsurface and receiving the returning pulses that have reflected off interfaces between materials with different electromagnetic properties (Figure 1). Antennas are moved across an area with a continuous series of radar pulses, giving a profile of the subsurface.

The key material properties are the dielectric permittivity, the electrical conductivity, and the magnetic permeability. These control the velocity with which the radio pulses travel through the material and the decay in amplitude of the pulse with distance. The pulse travels faster through a low dielectric permittivity material than a material possessing a higher dielectric permittivity. In contrast to permittivity, the conductivity of the material dictates how quickly the pulse of radio energy decays in amplitude (attenuates) with distance and thus controls how deep the pulse will penetrate. These two properties are mostly independent. For example, freshwater and salt water have essentially the same dielectric permittivity (salt water is slightly lower); however, salt water exhibits a much higher conductivity than freshwater. GPR pulses travel at similar speeds through both types of water; however, in salt water the energy is attenuated very quickly and does not penetrate deeply.

Reflections of the GPR pulse occur at boundaries in the subsurface where there is a change in the material properties. Only a portion of the pulsed signal is reflected and the remaining part of the pulse travels across the interface to again be reflected back to the receiver from another interface boundary. The time the pulse takes to travel through the layer and back is controlled by the thickness and properties of the material. The travel time between upper and lower boundaries of a layer can be used to calculate the layer thickness employing a known velocity.

GPR Equipment for Railroad Applications

Antennas are used to transmit and receive the radar pulses. The antennas are controlled by the GPR control unit, which also measures the time and amplitude of the returned signals. Antennas are designed to operate at various frequencies from tens of MHz (megahertz) to several GHz (gigahertz). The antenna's appropriate operating frequency must be considered for the particular investigation. The antenna choice must take into account the trade-off that exists between resolution and depth of penetration. The higher the antenna frequency is the greater the resolution; but higher frequency antennas have less depth of penetration compared to lower frequency antennas. Lower frequency antennas penetrate deeper than those at a higher frequency, but they have reduced resolution.

A second consideration for antenna selection relates to how the antenna is deployed. The two basic categories of antennas are air-coupled and ground-coupled (Smith, 1995). Antennas that are air-coupled are designed to be used suspended above the ground surface, with an air gap. Ground-coupled antennas are designed to be in direct contact with the ground surface, with no air gap. Air-coupled antennas are particularly suited to railroad applications since they are suspended above the ground and thereby allow high-speed measurement as well as clearance for objects such as turnouts, grade-crossings, wayside detection devices, and trash.

For this railway GPR development project, three sets of GSSI 4208 1-GHz horn antenna pairs are used. A pair of antennas is deployed outside each rail at the ends of the ties, and a third pair is positioned between the rails along the centerline of the track. The antennas are supported on an adjustable frame that is mounted on a hy-rail vehicle, as shown in Figure 2.

The frame is made of high-strength fiberglass tubing to minimize the interference that would occur from a metal frame. This arrangement permits three profiles to be collected at the same time as the pairs of antennas are moved along the track. That provides three continuous parallel longitudinal images along the track, providing information on the cross-track variability. Initially, the data were processed on a computer off of the track after data acquisition, with the result available within a few hours; however, a current research goal is to develop data processing software that will produce substructure conditions in real-time. The GPR data collected on railroad track is processed to remove the effects of the ties and running rails to produce a clearer image of the substructure conditions.

An accurate accounting of the locations of the GPR measurements is critical to an effective investigation. The system employs an integrated wide area augmentation system (WAAS) differential global positioning system (DGPS), and a distance measuring instrument (DMI) synchronized with the vehicle transmission. The DGPS can provide location information with accuracy error of less than 3 feet, but it can be adversely affected by bridges, tunnels, and radio frequency interference. The DMI provides continuous positioning information to supplement the DGPS data, but with an accumulating error of about 0.2%. Digital video images of the track are collected to further refine location information through identification of fixed assets along the track. The DGPS data are verified against 1-meter USGS aerial digital orthophoto quadrangle maps.

Processing and Modeling

To achieve the required radar information, the collected data need to be processed and modeled. Processing consists of the following steps:

1. Adjust the distance scale
2. Remove unwanted background and objects
3. Check accuracy of data

Modeling produces quantitative values of dielectric permittivity, water content, layer dimensions, and unit weight.

The GPR data are modeled by matching simulated radar pulses to the measured radar pulses. The layer dielectric permittivity versus depth in the simulated pulse that produces the model matches represents the properties of the track substructure layers.

Water content and unit weight were calculated using relationships between them and the dielectric permittivity. To verify and calibrate the railway GPR data, inspection trenches were dug in locations with key substructure conditions. This required real-time data processing into images to locate suitable places to trench. Depths to key substructure layers were then measured in the trenches and used with travel times from the radar data to determine average velocities. The velocities are used to calculate the dielectric permittivity values.

Providing automatic modeling is desirable to derive dielectric properties and then extract density and water content information (Olhoeft and Smith, 2000)**.** This is now done for concrete and asphalt highway surveys (Olhoeft, 2000)**.** However, the railway situation is more complicated than highways because highways have a flat, smooth, horizontal surface that is easily calibrated for absolute amplitude. Railway ballast is coarse gravel with a slope and surface roughness comparable to the scale of the 1 GHz wavelength. Thus the smooth surface calibration assumptions do not work.

The steps of automatically processing ground penetrating radar data from raw data with distortions as acquired to geometrically correct images are known and straightforward. The data acquisition process needs to be standardized for uniform acquisition of GPR data (in terms of procedures, time and relative amplitude calibration, antenna geometry and polarization) and location information. The location or position information would be best done using the global positioning system and preferably differential GPS with a base station and a roving station on the GPR system. However, GPS does not work everywhere, so a backup positioning system will be required. The data processing then easily becomes automatic to correct for distortions and common acquisition problems. With calibrated time and position, the GPR data can use diffraction hyperbola and other velocity determination estimates to scale both vertical and horizontal axes to produce geometrically correct image cross sections of the subsurface. This much was demonstrated in the Phase 2 work. Also, Phase 2 showed how to polarize and locate the GPR antennas to minimize the reflections from the metal rails.

This standardization of the data acquisition process requires acquiring data in the field and learning about the things that will cause problems and need to be dealt with in data processing. Examples would be places where the GPS does not work (urban areas, tunnels) and alternative positioning systems will be required (track wheel, inertial guidance, etc.), how to recognize and handle radio frequency interference problems caused by railroad communications appearing in the GPR data, how to recognize and flag places where GPR does not work (no penetration through clay layers, metal, or highly conductive salt zones), and other unanticipated issues.

Once GPR data are processed to geometrically correct image cross sections of the track substructure, then image processing and texture, morphological or pattern recognition algorithms are applied to automatically enhance, detect and extract geometric features of interest. These features would include detection and mapping of ballast and other layer thicknesses, location of abrupt thickness changes (like a shear key), location of material changes (such as type of ballast), location of tie type and quality (wood versus concrete), location of utilities (such as cable and pipe crossings), location of drainage features, and so forth.

Also, once geometrically correct GPR data are available, the next requirement is to calibrate the absolute amplitude of the data so as to allow full waveform modeling and extraction of subsurface physical property information. This will allow determination of electromagnetic properties of the subsurface through electromagnetic modeling, followed by conversion through mixing models to subsurface quantitative density and water content maps. Such absolute amplitude calibration is easily done for smooth and flat surface concrete and asphalt roads (Olhoeft and Smith, 2000); (ASTM, 1999), but is not easily done for the rough and sloping gravel interface at the interface between air and railroad ballast (which is rough at the radar wavelength). An absolute amplitude calibration procedure using multiple antenna geometries, polarizations, and/or frequencies will be required to be developed. Once the absolute calibration procedure is available, the automatic modeling becomes straight forward, as is done for concrete and asphalt roads (Olhoeft and Smith, 2000). The problem is to determine the minimum combination of things required for an adequate absolute amplitude calibration, and then to build that calibration requirement into the standardized data acquisition procedures. The automatic processing and modeling algorithms will also require the development of data quality and consistency tests prior to processing and modeling to confirm the data were acquired in a known manner without added surprises. This will also allow quantitative confidence information to be presented with the final thickness, density and water content determinations.

Application to Railways

The track substructure, consisting of the ballast, subballast, and subgrade layers, has a profound influence on track performance. Accurate knowledge of the substructure condition is important in effectively assessing the potential for service interruptions and the need for slow orders. A significant part of a railroad's track maintenance budget is allocated to correct rough track that is caused by movements in the substructure under repeated train loading. The substructure performance is significantly affected by moisture accumulation and thickness of the roadbed layers (Selig and Waters, 1994). Thus the hidden and hard-to-monitor substructure conditions are important to railway track performance.

Appropriate tools for field investigation of railway substructure problems include cross-trenches, cone penetrometer tests, test borings, characterization of track geometry data and deterioration trends, track stiffness measurements, and ground penetrating radar (Selig, 1997), (Hyslip and McCarthy, 2000). GPR surveying provides a continuous survey and characterization of the track substructure, quickly locating areas of potential trouble for further investigation or maintenance.

Material and moisture variation within the track substructure cause distinct dielectric property differences that are recognized by GPR. Water has the highest dielectric permittivity of the materials found in the substructure and produces a strong effect on the GPR profiles. In an area where water has been trapped in the substructure, the dielectric permittivity is increased, resulting in a stronger reflection than if it were dryer. The texture of the radar record allows the relatively coarse-grained ballast layer to be recognizable from the comparatively finer-grained subballast layers. Likewise, subgrade material is typically very distinct from the upper granular layers. In the case of fouled ballast, the normal layering is disrupted by fine-grained materials in the otherwise coarse-grained matrix. By quantifying the GPR pattern scattering textures, determinations can be made regarding the amount of fouling in the ballast layer.

The GPR profiles are manipulated to extract layer thickness and permittivity (related to the material density and water content). In addition, the profiles are examined to determine anomalous variability in contrast and texture, and relate these anomalous areas to the presence of fouled ballast.

To verify and calibrate the railway GPR data, it is currently necessary to excavate cross-trenches (inspection trenches) in locations with key substructure conditions to correlate the actual conditions with the radar data. Figure 3 shows a typical GPR image example along a 500 ft section of track. Figure 3 also shows photos of the cross-trenches that were excavated and logged for calibration of the GPR data. Depths to key substructure layers are measured in the cross-trenches and used with travel times from the radar data to determine average velocities. The velocities are use to calculate the material properties values such as dielectric permittivity.

Once enough GPR data has been calibrated with inspection trench information, the need for inspection cross-trenches will diminish from what is presently required. Eventually, quick assessments of subsurface conditions over large distances will be made with minimal invasive cross-trenching.

Development of Performance Indices

Rough ballasted track is often caused by the poor condition of the track substructure (ballast, subballast and subgrade) under repeated train loading. The experience of Ernest T. Selig, Inc. (ETSI) has indicated that the majority of track substructure problems in the US are associated with one or more of the following:

- Poor drainage of ballast, subballast and subgrade as indicated by:
  - Trapped water in ballast and subballast.
  - Layer depression in impermeable subgrade.
- Fouled ballast (causing rapid loss of surface after maintenance).
- Subgrade failure or deformation (from progressive shear or excessive plastic deformation).
- Subgrade attrition (due to lack of subballast).
- Subgrade excessive swelling and shrinking (expansive clays).
- Longitudinal variation of the condition and behavior of the track substructure.
- Transitions (causing loading and stiffness discontinuities).
- Unstable embankments.
- Inadequate amount of crib and shoulder ballast.

Each of these substructure problems can be defined in terms of one or more of the following condition indicators of the ballast, subballast and subgrade:

- <u>Layer</u> extent
  - thickness
  - lateral and longitudinal extent

  – deformation with time

- Water content
  – trapped water
  – moisture content
  – change with time

- Composition
  – fouling condition
  – gradation
  – in-place density/consistency
  – ballast type (e.g., basalt vs. limestone)
  – soil type (e.g., clay vs. sand, also strength, compressibility, load history)

Measurement and monitoring of many of these key substructure condition indicators using ground penetrating radar (GPR) can provide numerical data for development of substructure condition indices. The following Table 1 presents the various substructure problems and the corresponding GPR information that can be measured for use in developing condition indices.

Table 1: Substructure Problems and Corresponding GPR Measurement.

Substructure Problem	GPR Indices Based On:
Poor drainage – trapped water	Intensity of GPR reflection and moisture contents of ballast/subballast layers.
Poor drainage – layer depression (bathtub)	Difference in depth to impermeable subgrade surface laterally across the track.
Fouled ballast	GPR pattern scattering textures and permittivity of ballast layer.
Subgrade failure or deformation	Ratio of layer thickness and/or subgrade surface depth from middle to edge of tie. Also, moisture content & consistency of subgrade soil along with thickness of granular layer.
Subgrade attrition	Lack of subballast layer
Subgrade excessive swelling and shrinking	Variation of clay subgrade surface. Also, moisture content and consistency of subgrade soil.
Longitudinal variation of the condition	Variation (roughness) of layer thickness, moisture content, composition.
Transitions	Site specific.
Unstable embankments	Typically, the present GPR system is not applicable due to shallow penetration (<2m). Some indication of shallow manifestation of layer deformation may be possible.
Inadequate crib and shoulder ballast	This can be done without GPR by viewing/inspection of ballast surface.

At this point in the GPR development for railroads, GPR can provide quantified information on substructure ***layers*** (thickness, lateral/longitudinal extent, and changes in layers from repeat surveys over time), and the presence of trapped ***water***. The continued development will soon produce the ability to quantify the moisture content of various substructure layers. Many of the ***composition*** variables of the substructure layers can eventually be determined from GPR data using modeling techniques. In particular, we are currently working on methods to determine the fouling condition of the ballast by modeling the scattering textures of the GPR scans.

Examples of Subsurface Radar Images

General indices of track substructure condition can be based simply on the longitudinal and lateral variation of layers, water and composition. The longitudinal variation of substructure layers often results in track stiffness variations, which translates into rough track. Examples of general indices based on longitudinal variation of layers are presented in Figure 4 and Figure 5**.**

The GPR image in Figure 4 is an ORIM screen grab of an almost 2 mile section of track. The distance to the bottom of the granular layer was manually digitized (shown as white points on the GPR gray-scale image). This data were then converted to a continuous index representing layer variation by averaging over a 1000-ft moving window to give a continuous "roughness" value of the subgrade surface elevation. This index is shown on the bottom plot in Figure 4. The index is high on the left side of the plot where the subgrade surface elevation is variable. The index is low on the right side of the plot where the subgrade surface is relatively uniform.

A similar general index based on moisture content can be determined in the same manner. Eventually, once the modeling development work is further along, the variation in layer composition can be quantified in much the same way. These types of general indices can be integrated with geometry and maintenance records and then used for broad assessment and system wide prioritization. These indices can be further enhanced by comparing aerial soil/geologic maps with BNSF route layout to delineate the major areas representing different substructure conditions.

An example of a more specific index, based on layer detection, is subgrade layer depth variation for ballast pockets is shown in Figure 5.

Other specific indices can be developed based on the lateral variation of layers. For instance, the lateral variation of the subgrade surface across the track is indicative of poor drainage due to bathtub condition and subgrade failure/deformation. Figure 6 shows a typical track cross-section with deforming subgrade. The arrow dimensions are located at the GPR antenna locations.

Figure 7 shows actual longitudinal scans for approximately 1000 ft of track. The distance from the datum to the top of the subgrade surface is indicated by the white arrows. Locations A & B are where the subgrade soil has deformed upwards, creating a situation similar to that shown in Figure 6.

Figures 4 through 8 are a few samples of the track substructure indices currently being developed. These simple indices will be refined to include weighting factors, combined with other information such as geometry and climate data. Indices can also be developed based on changes in layer and water over time.

In general, indices can be based on processed, without modeling the data. These types of indices are based on:

- Individual condition indicators
- Composite parameters to represent individual substructure problems **(**Table 1: Substructure Problems and Corresponding GPR Measurement.**)**
- Composite parameters to represent several problems.

Indices can also be based on processed but not modeled data. These indices would incorporate calculated water content and other composition parameters, and could be used to develop more accurate composite indices. Both of these types of indices possibilities are being considered. These will not all be developed as part of this current project but we will pursue those that are most appropriate.

In the following examples the horizontal scale is about 300 ft (92 m) and the vertical scale is almost 6.5 ft (2 m). The two GPR cross-section images shown in Figure 8 are from the same location, but opposite sides of the track. The sand zone shown in the top scan acts as a water pocket, and the trapped water in this pocket softens the surrounding clay subgrade causing track geometry deterioration. The shear key in the bottom image was a previous attempt to stabilize the soft subgrade by digging a drainage trench into the subgrade clay and filling it with ballast. The extent of the shear key is well defined by the increase in ballast thickness and absence of the subballast layer.

Figure 9 shows an example of the subsurface conditions at highway grade crossings, as detected by GPR. Trapped water immediately adjacent to the crossing is apparent. The decrease in GPR reflection amplitude progressing away from the crossing indicates decreasing water content of the subballast and subgrade. The strong reflection from the surface of the reinforced-concrete crossing planks momentarily reduced the signal amplitude from the subsurface layer compared to the open track.

The scan in Figure 10 shows the varying thicknesses of ballast and subballast which, in this example, is an indication of a problem associated with lateral subballast spreading on top of a clay subgrade. This occurred because the clay surface softened to a tooth paste consistency from the presence of water and the repeated train loading.

The scan in Figure 11 shows the access road along one side of the track. The variable thickness of the gravel surface layer is installed clearly shown. Also shown are drainage pipes from under the track installed in trenches dug into the road subgrade.

Figure 12 shows a V-shaped ditch that was dug perpendicular to the track I the bottom image to drain trapped water from the track. The center image shows a greatly reduced ditch depth and the top image shows a wet spot on the opposite side of the track from a deep V-drain. Using and estimated ballast dielectric permittivity from the radar travel time to the bottom of the V-shaped ditch, the ditch depth was estimated at 4.7 feet (1.4 m). The image of the bottom of the ditch is brighter than the ballast/subballast boundary which indicated that the bottom of the ditch is wetter. The north side of the wet spot has the texture and periodicity corresponding to the tie spacing. Excavation of a similar image in another location showed this pattern to be caused by fingering of the subgrade clays under the repeated loading of the passing trains.

Figure 13 shows the variation in the ballast thickness at the two ends of the ties. The ballast layer becomes thin at the center of the image. The bottom of the ballast layer is above the bottom of the tie in the center of the lower image.

Substructure Management Using GPR

GPR data have been used in site-specific engineering investigations to determine root-cause of specific problems and develop engineering solutions at specific locations. The present ongoing project is also developing condition indicators and performance indices based on the GPR measurements. GPR is particularly useful for large-scale surveys to develop subsurface indicators for wide-area planning and allocation of resources.

Figure 14 shows a typical example of the subsurface conditions along three parallel longitudinal profiles at two road grade-crossings, as detected by GPR. Trapped water immediately adjacent to the crossings is apparent in the images. This water is trapped due to nonexistent lateral drainage out of the track. The low point on the relatively impervious subgrade surface is shown about 300 ft to the left of the main road crossing. This information is useful for the design of an effective drainage system that will improve the subsurface condition and to thereby solve a chronic maintenance problem. In this case, the GPR indicates that the trapped water can be drained longitudinally away from the crossings to a positive outlet point, as depicted on the bottom image in Figure 14.

GPR Substructure Indices

One approach to developing meaningful substructure indices based on GPR requires matching the information from the GPR measurements to known characteristics of different types of substructure problems and then quantifying the GPR data to depict these characteristics. An example of this approach can be seen in Figure 10**.**

Figure 10 shows a GPR scan with a varying thicknesses of ballast and subballast which, in this example, are an indication of a problem associated with lateral subballast spreading on top of a clay subgrade. The problem with the spreading subballast shown in Figure 10 was prevalent throughout a 2-mile section of track. GPR data were used to develop an index based on the relative thicknesses of the ballast and subballast layers. The index is shown as a continuous trace on the middle plot in Figure 10, and as a "bar code" image in the bottom plot. The bar-code image is a convenient way to view the extent of the problem for a particular section of track. The dark bands in the bar-code image indicate areas where the subballast has thinned considerably, and similarly, the lighter banding indicates less thinning. Remedial work was planned based on the condition of the track as depicted by the bar-coded image.

Another example of a condition index based on GPR information is depicted in Figure 5. Figure 5 shows three parallel longitudinal GPR profiles indicating ballast pockets that have developed in an embankment under the influence of heavy axle load traffic. A ballast pocket is formed by the greater load-induced settlement of the subgrade surface directly under the track. As downward infiltrating water ponds in the depression that is created, the fill continues to soften and further deformation occurs. As the track settles due to the fill deformation, additional ballast is added and tamped under the ties to raise the track, resulting is a thick ballast pocket. A common, simple remedy to minimize the continued development of the ballast pocket is to drain the ballast pocket with a cross-drain (essentially a ballast-filled trench) excavated perpendicular to the track. GPR can delineate the bottom of the pockets to ensure that lateral drainage is put at the most effective location, i.e., at the lowest point of the ballast pocket.

The banded image in the bottom of Figure 5 shows the depths of the subgrade surface added together in order to accentuate the areas with the ballast pocket condition. This information is portrayed in the color-coded bar scale plot in Figure 5 which depicts the worst areas (deep ballast pockets) with dark banding and good areas with white.

Automated measurement and analysis techniques are being developed to produce quantitative indices of track substructure condition that will enable improved cost effectiveness of maintenance planning, increased safety, and reduced train service interruptions. These indices will be based on such things as layer contours, moisture content in the different substructure layers, and amount of fouling material in the ballast.

In developing wide-area indices, the Optram Right-of-way Infrastructure Management (ORIM) system is being used to help correlate the substructure characteristics derived from GPR with other measurements such as geometry, features, maintenance records, and other known subsurface conditions of the track. This allows seeing the relationship of GPR to track condition and features, as well as visualizing substructure effect on geometry trends and maintenance effort.

Conclusions

GPR images can give a good indication of the subsurface layer configuration, and patterns within the data can give a good indication of subsurface condition. GPR provides continuous, top-of-rail measurements of substructure layer conditions, with the potential to measure:

- substructure layer thicknesses;
- water content and density of the ballast, subballast, and subgrade;
- trapped water from poor drainage;
- soft subgrade from high water content;
- nonuniform and deformed substructure layers and variations in substructure conditions across the track (with multiple antenna pairs); and
- fouling condition within the ballast.

With proper application of GPR, very useful image cross-sections of the track substructure can be obtained which show variations in conditions along and across the track, and with depth, indicating differences in track performance. Simultaneous recording at the three transverse locations (both edges and centerline) offers significant advantages: track occupancy is greatly reduced and precise correlation between the positions is achieved.

Expected advantages and limitations of radar for railway applications

Advantages:

1. Provides a rapid, non-destructive measurement technique that minimizes the interference to train operation.
2. Provides continuous, top of rail measurements of substructure layer conditions.
3. Potential conditions that could be measured include layer thickness, water content and density. From these the type of material can be estimated. Trapped water from poor drainage should be observable. Fouled ballast should be distinguishable from clean ballast. Nonuniform and deformed substructure layers will be apparent.
4. Use of multiple antennas can provide variations in substructure conditions across the track.

5. Data can be collected at vehicle travel speeds in excess of 25 to 50 mph. However, as the speed is increased the spacing of the radar pulses along the track increases. The radar spacing can be decreased to compensate to some extent by increasing the pulse repetition rate (within limits expected to be imposed by the FCC).
6. Define lengths of track that have similar conditions and expected performance.

Limitations:

1. Substructure layer boundaries may not be visible to the radar under some conditions, such as:

    - Boundaries producing high reflections can mask radar signals from lower layers.
    - High moisture content or wet conditions can reduce the depth of radar penetration
    - Too little difference in electrical properties between the two adjoining layers
    - Highly conductive (salty or clayey) soils may limit radar penetration

2. Possible FCC regulation restrictions on use of 1 GHz antenna may require some equipment modifications.

The GPR measurements can be reduced to concise, useful values for developing performance indices and condition indicators. The approach to developing meaningful substructure indices based on GPR requires matching the information from the GPR measurements to known characteristics of different types of substructure problems, and then quantifying how the GPR data depicts these characteristics. This requires input from knowledgeable railway geotechnical engineers.

The GPR information needs to be calibrated to the substructure characteristics and also needs to be correlated with other measurements such as track geometry, features and track stiffness and maintenance records. The utility of predictive indices would be limited if based solely on GPR data.

Table 2 provides some examples of specific substructure problems and the corresponding GPR information that could be used to define the extent and severity of the problems.

Table 2: Substructure problems and related conditions.

Substructure Problem	Substructure Indices Based on
Subballast moving laterally on thin clay surface (e.g., Butte Sub MP439)	Change in layer thickness laterally across the track and presence of high moisture content layer
Progressive shear failure of subgrade	Ratio of layer depth from middle to edge of tie.
Highly-fouled ballast	Dielectric constant of upper part of ballast layer.
Poor drainage	Moisture contents for various layers, layer depressions, and intensity of radar reflection.

Aside from use in performance indices, GPR also provides information for diagnosing causes of problems at specific locations, (e.g., ballast pockets, soft clay, and for developing engineering solutions). GPR is very complimentary to other investigation tools such as cross-trenches and track stiffness measurements.

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Stewart Newman of ETSI assisted with the data processing. Tom Selig of ETSI prepared the figures and manuscript. BNSF Railway staff participated in the field work.

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Figures

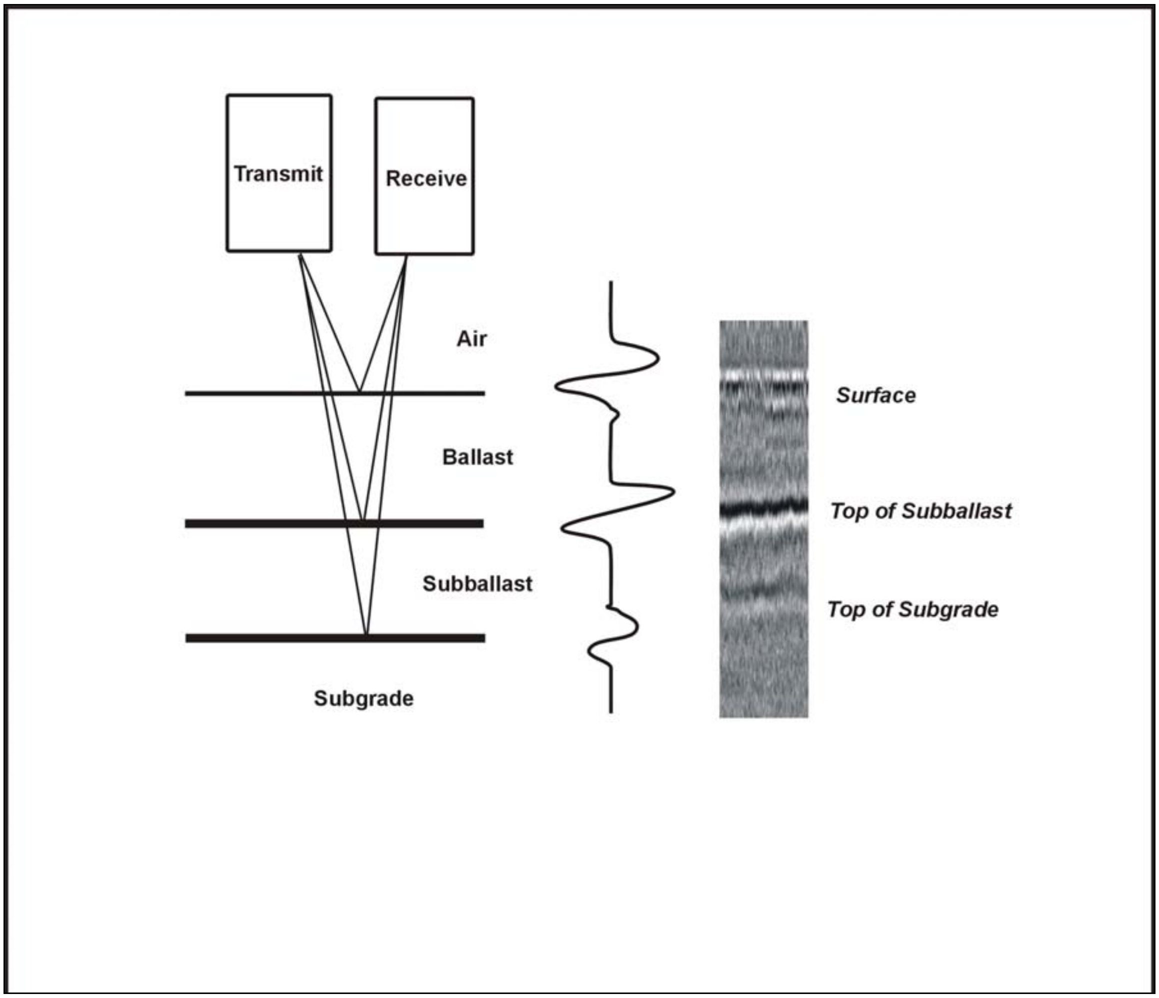

Figure 1: The generation of a GPR profile. (a) Transmitted energy is reflected off the boundaries in the substructure. (b) A single trace or scan composed of the reflection amplitudes as a function of time for the reflections in (a). (c) Adjacent scans are combined to build a profile.

Figure 2: GPR Hy-Rail setup with three pairs of 1-GHz horn antennas.

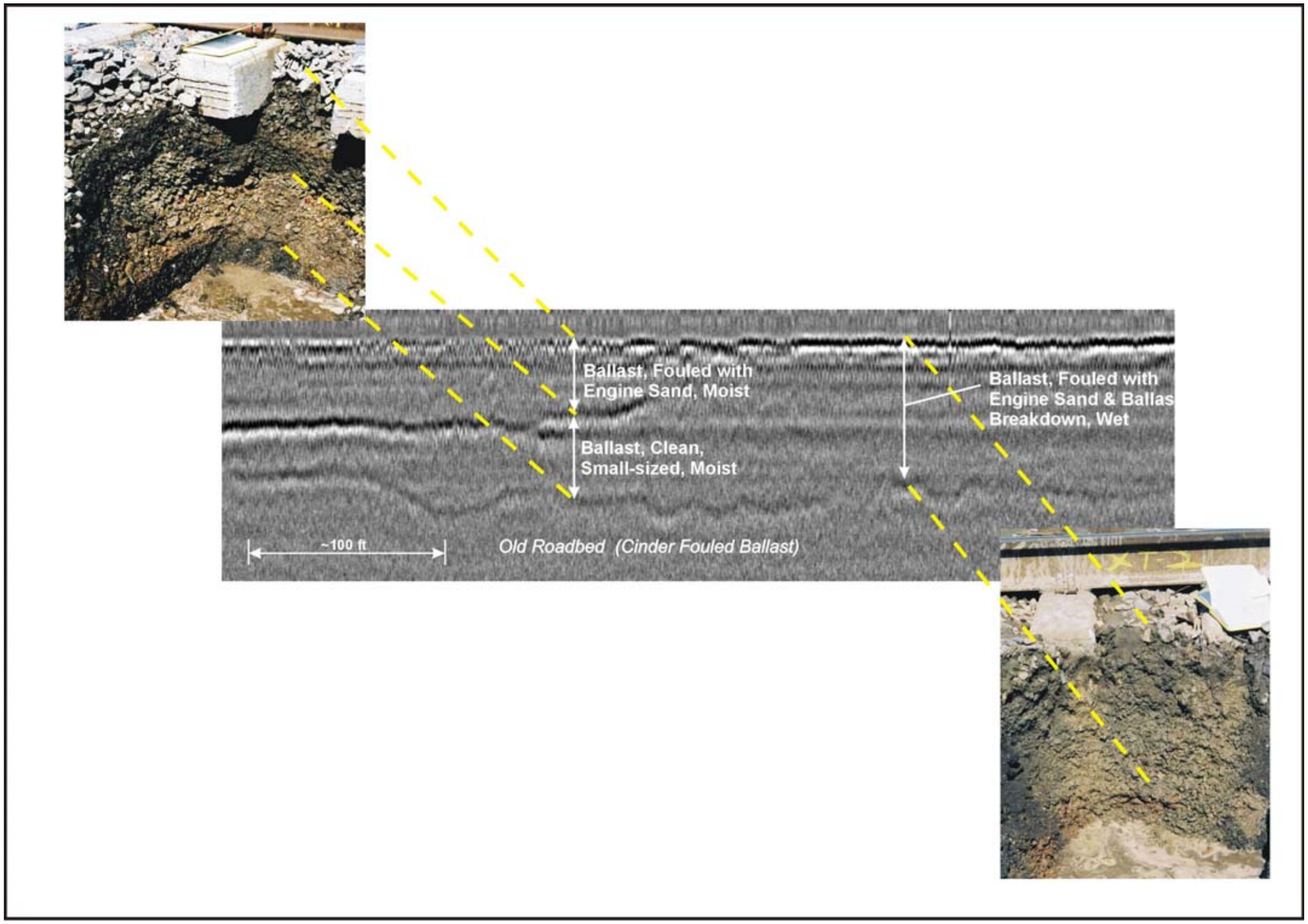

Figure 3: GPR image example with cross-trenches for calibration.

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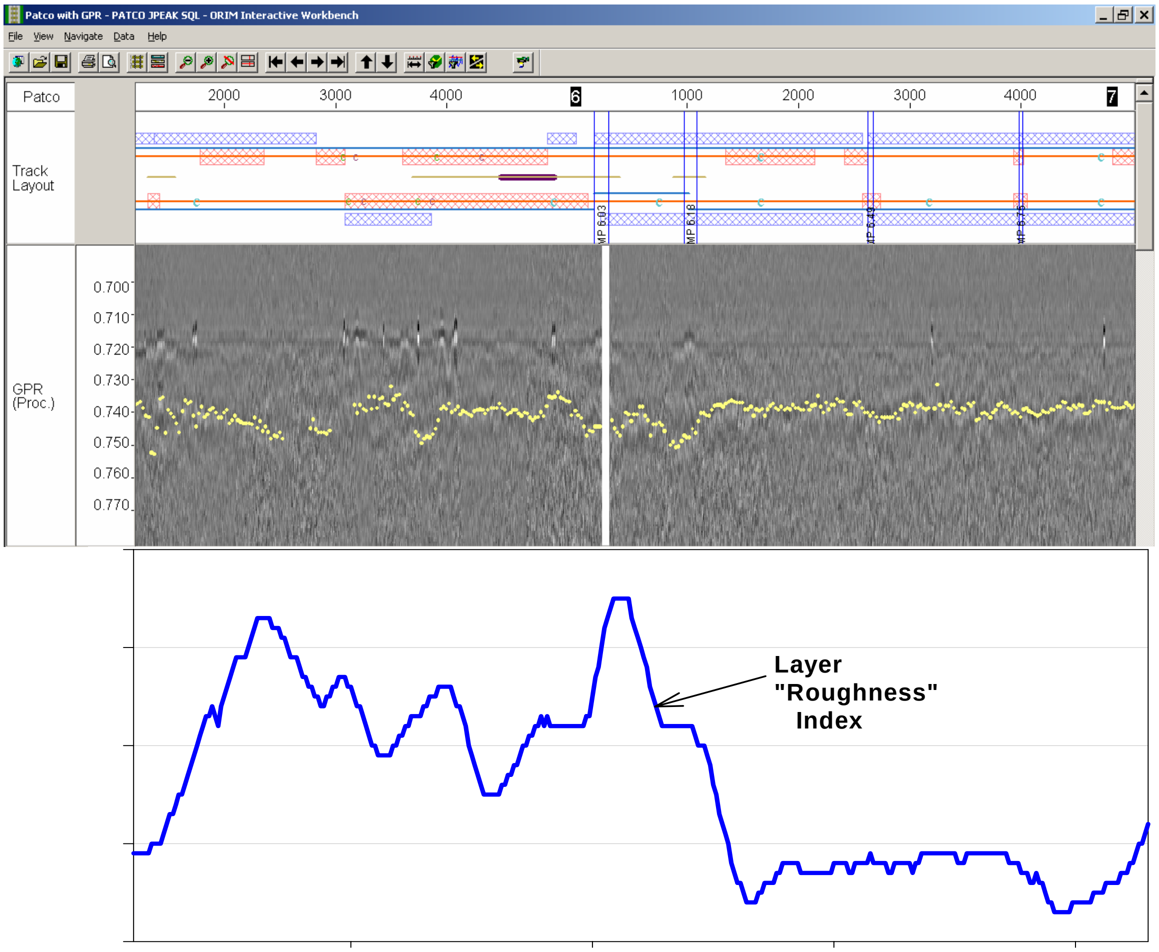

Figure 4: Example of Layer Based Index of Longitudinal Layer Variation.

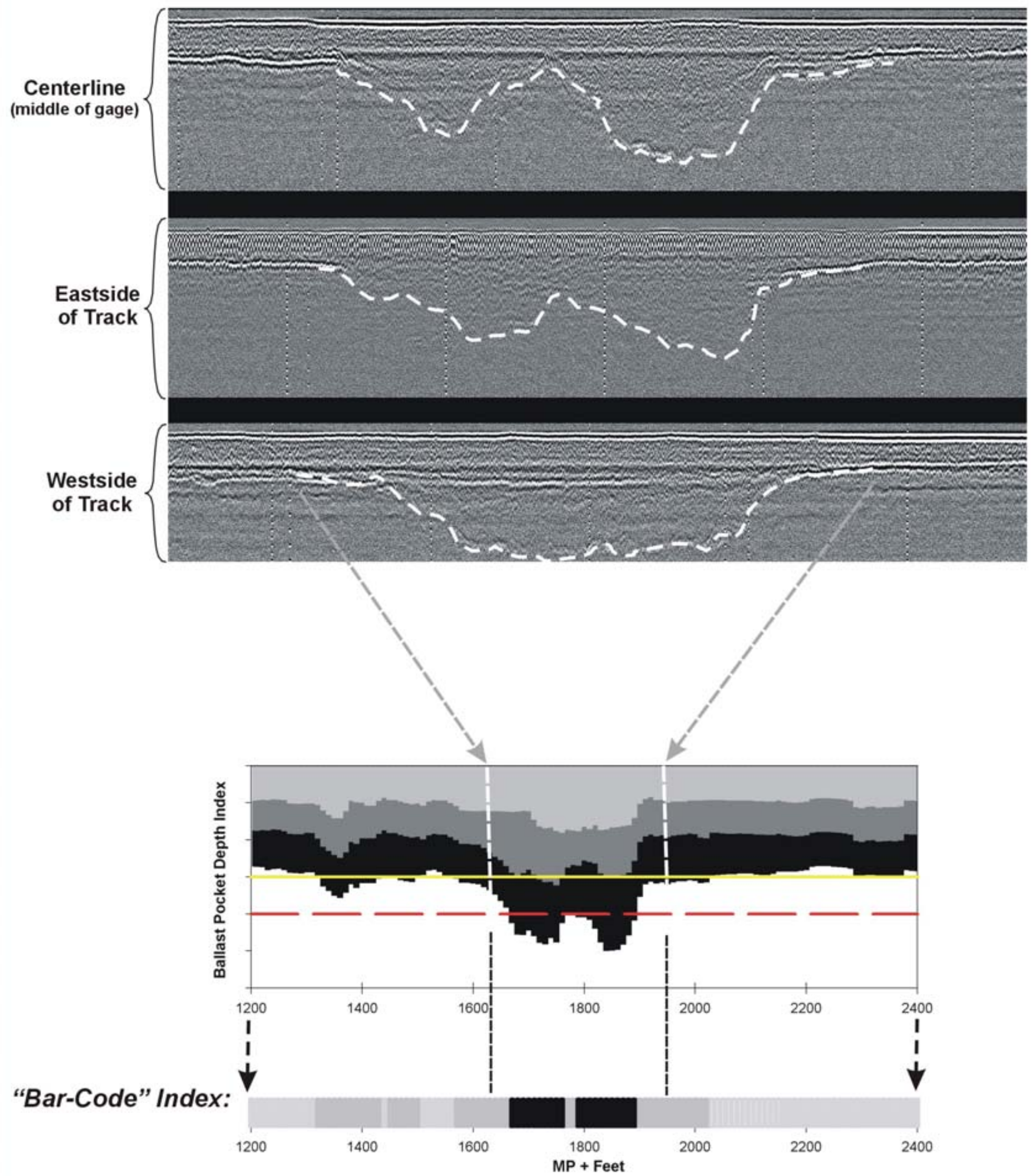

Figure 5: Subsurface Index based on depth of ballast pocket.

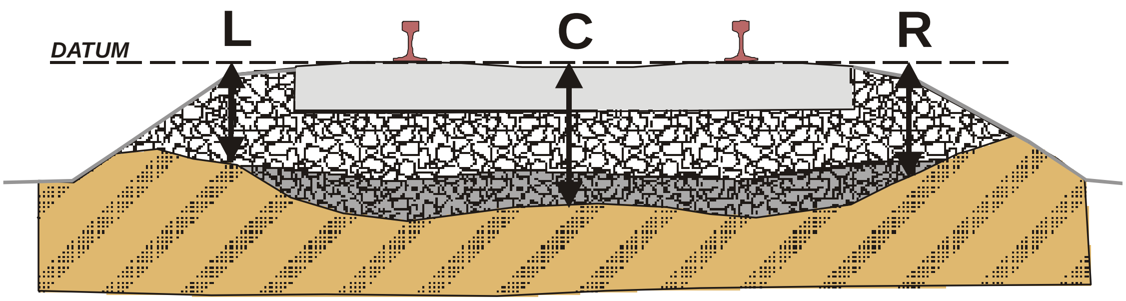

Figure 6: Typical track cross-section with subgrade deformation.

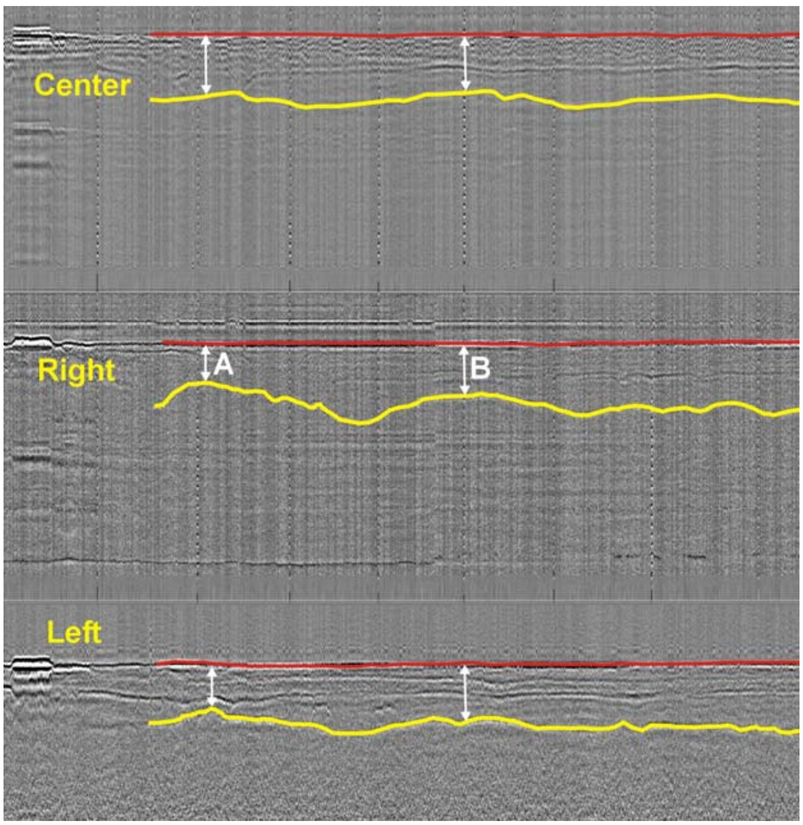

Figure 7: Three parallel GPR scans showing subgrade deformation.

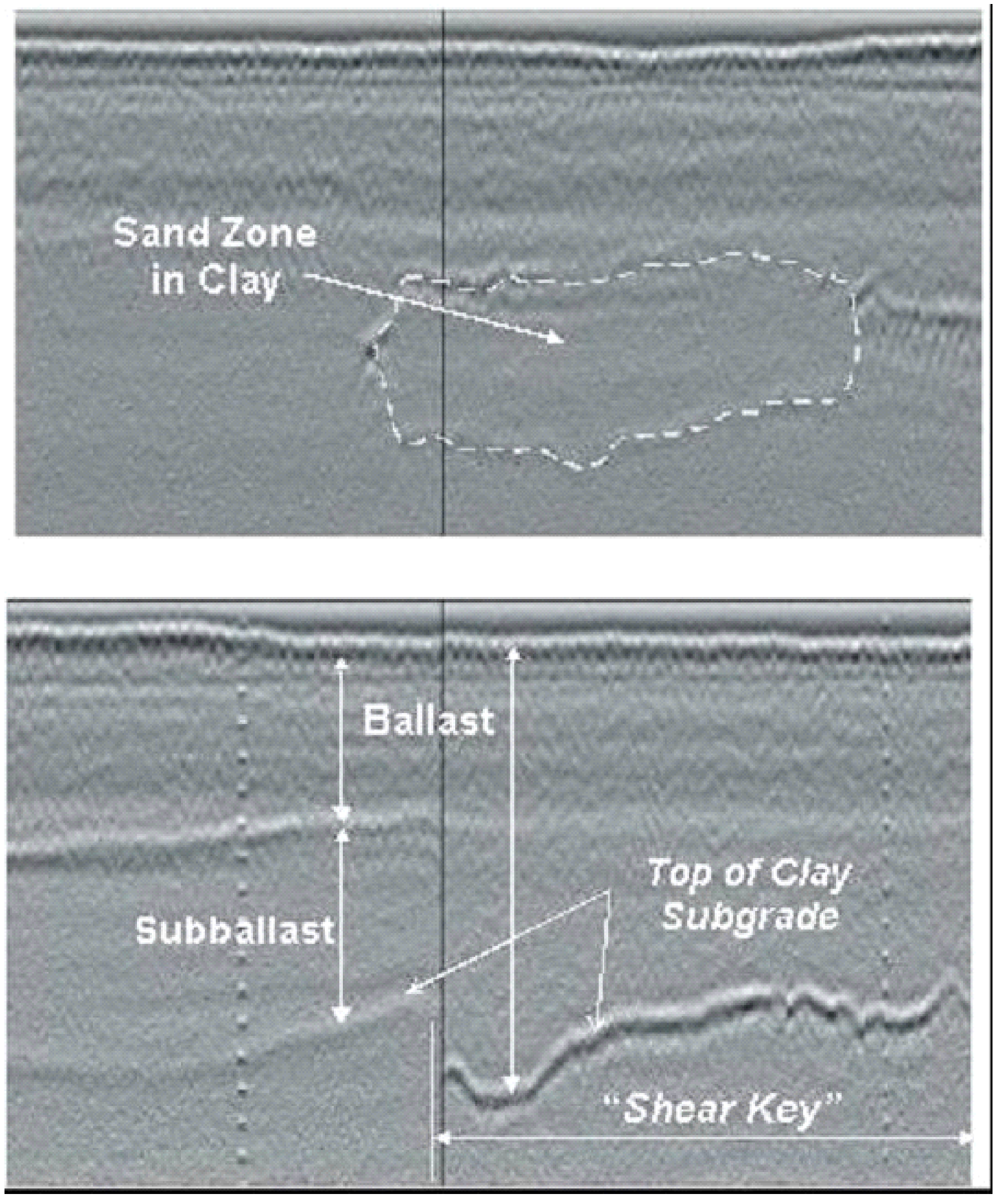

Figure 8: GPR scan showing sand pocket and shear key.

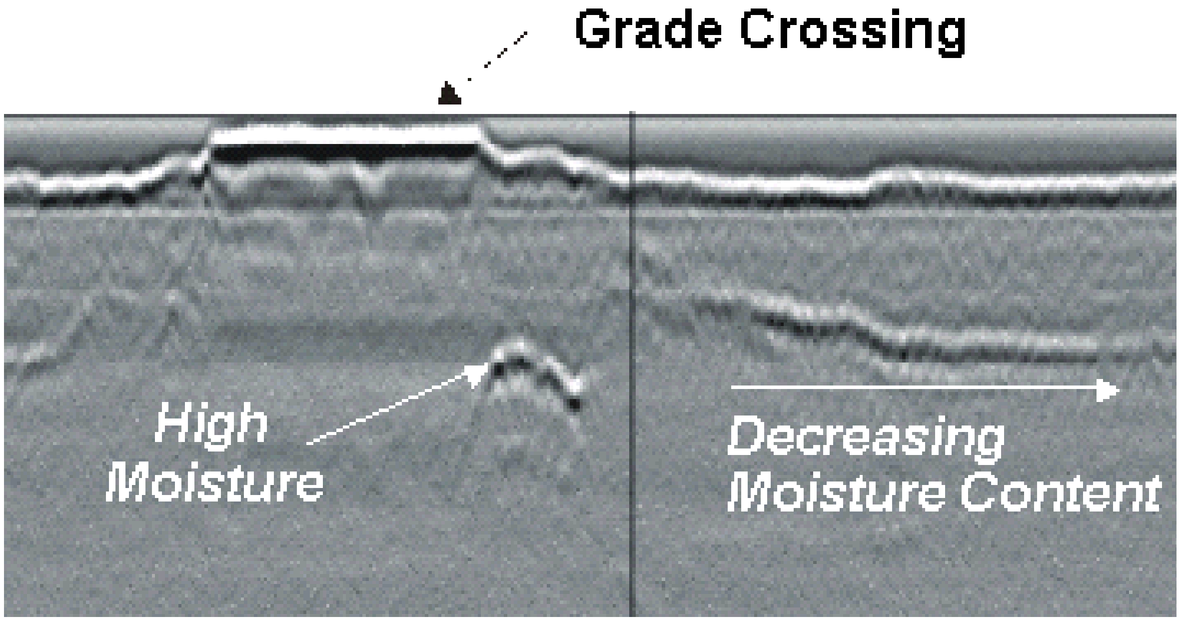

Figure 9: GPR scan at highway grade crossing.

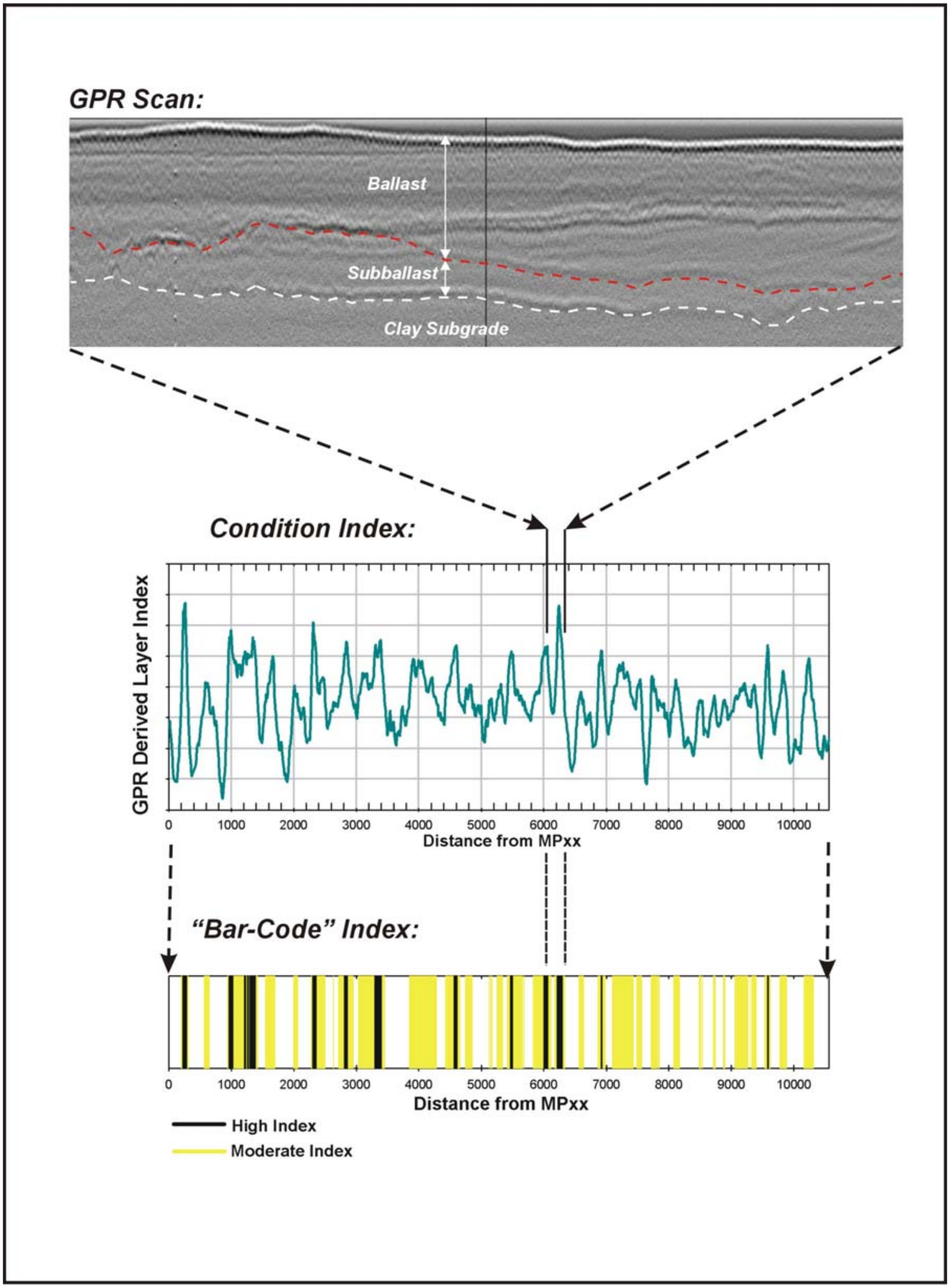

Figure 10: Subsurface Index based on thinning subballast condition.

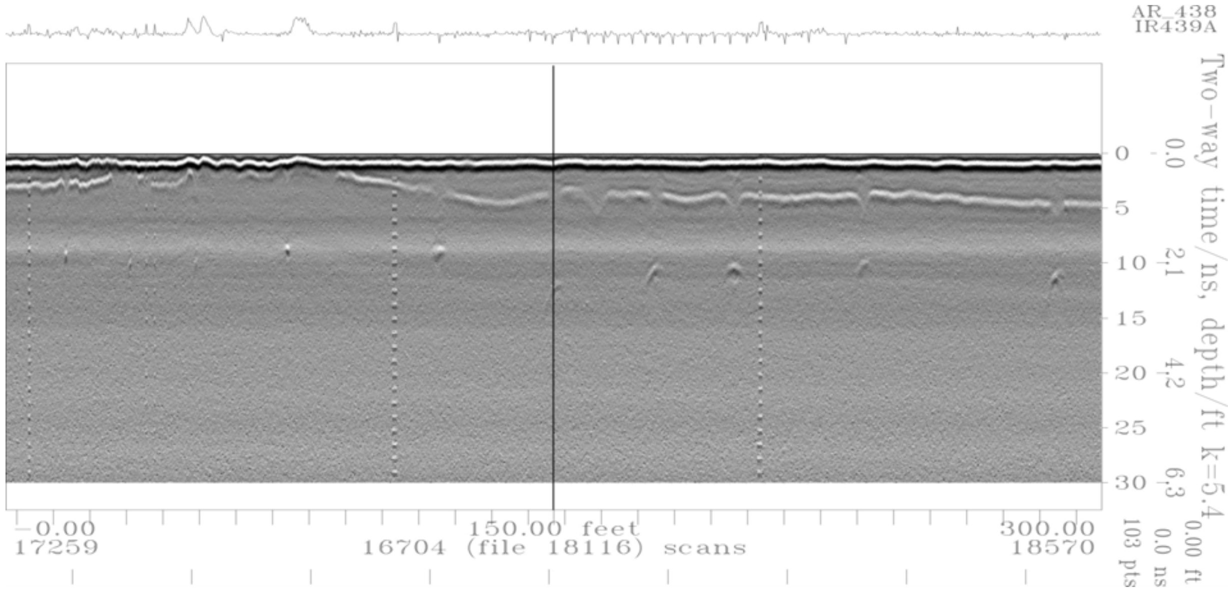

Figure 11: GPR image of access road along track.

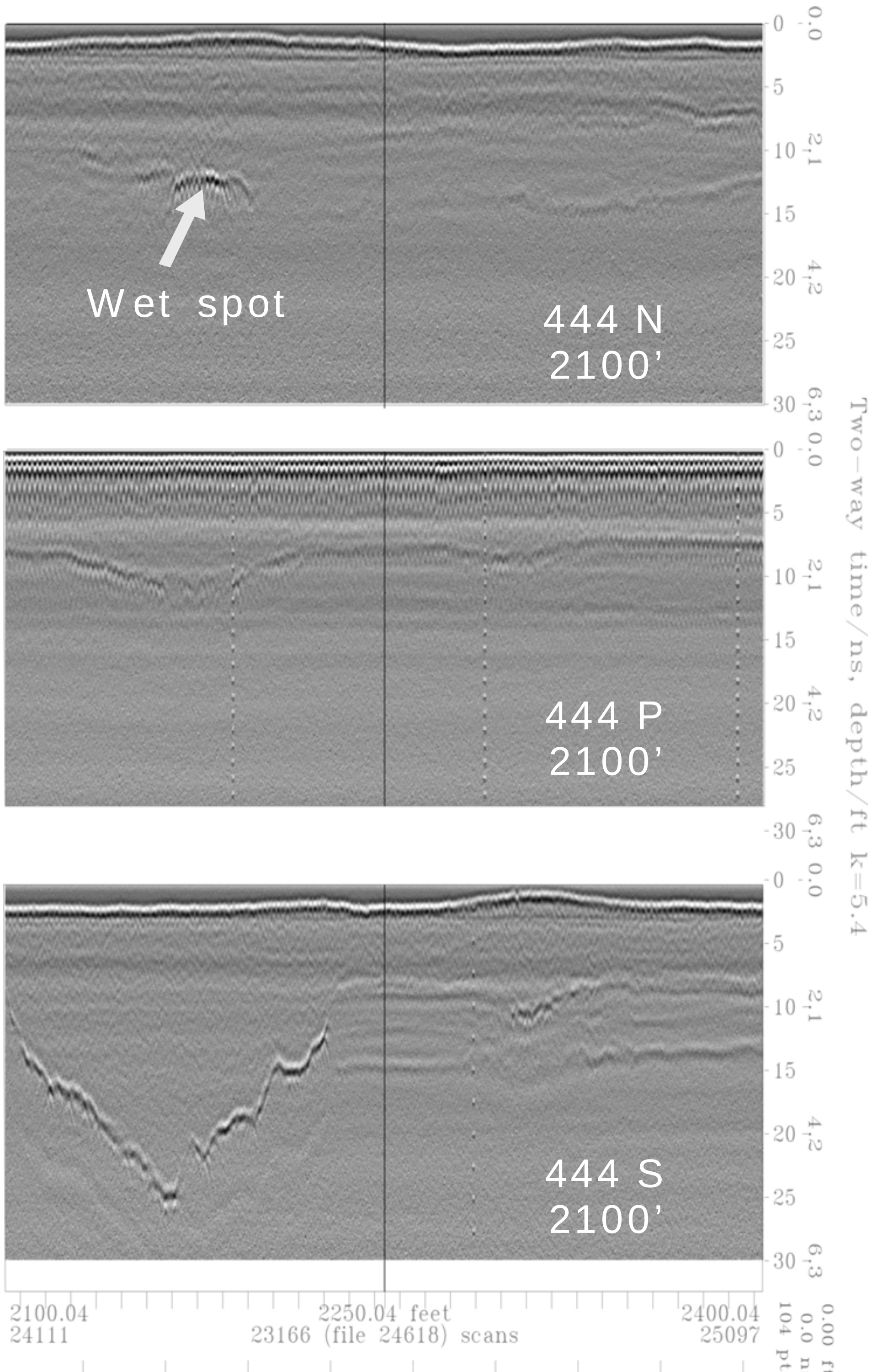

Figure 12: Comparison of images on the two sides and the center of the track substructure.

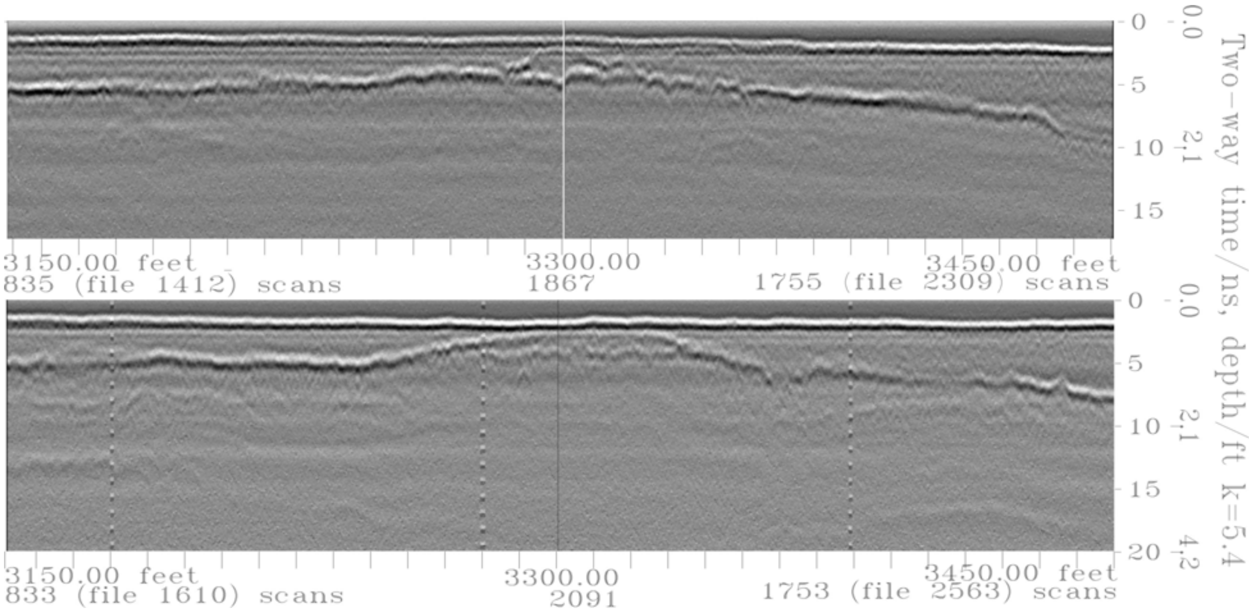

Figure 13: Reduced ballast layer thickness.

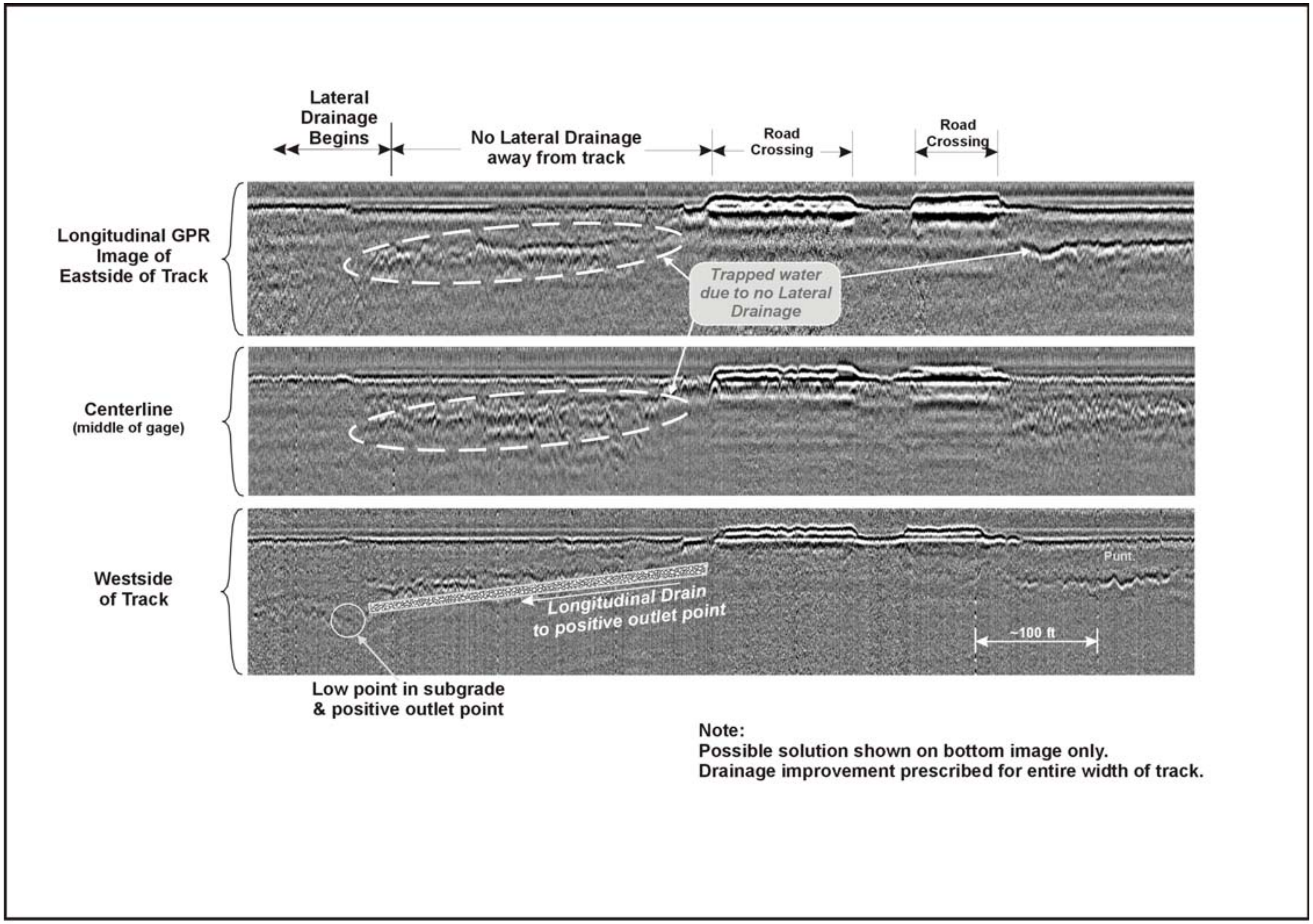

Figure 14: Three parallel, longitudinal GPR images near two road-crossings.